Water Science and Engineering, 2010, 3(1): 67-74
doi:10.3882/j.issn.1674-2370.2010.01.007

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Improved design of guide wall of bank spillway at Yutang Hydropower Station

Ji-bao WANG*[1, 2], He-chun CHEN[2]

1. College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing 210098, P. R. China
2. College of Hydraulic and Environmental Engineering, Three Gorges University, Yichang 443002, P. R. China

Abstract: Ensuring that water flows smoothly into spillways is the main challenge in spillway design. In order to help avoid the formation of vortices and separation of flow along the guide wall in front of the gates during overflow through the spillway, an experiment with a physical model of the Yutang Dam bank spillway was carried out. The profile of the guide wall was redesigned to eliminate the formation of vortices and separation of flow. This involves opening up holes in the middle part of the guide wall. The test results show that the design is effective in improving the flow conditions of the inlet, and in ensuring the desired values of water head along the guide wall and discharge capacities of the spillway.

Key words: *physical model; bank spillway; guide wall*

1 Introduction

A spillway is a hydraulic structure that is usually provided at storage and detention dams to release surplus or flood water that cannot be safely stored in the reservoir in order to prevent damage to the dam. The failure of dams may cause serious loss of life and property. Spillways of improper design or insufficient capacities have caused failures of dams. For an earth and rock-fill dam built in a narrow gorge with no suitable site for the spillway, a riverbank spillway is often adopted. In general, separate structures are required for the bank spillway and the dam. This results in crossflow when water passes the weir of the spillway, which in turn causes flow separation at the bank of the inlet channel, leading to the formation of eddies. If the velocity is high, vortices can also appear in the front of the inlet, which should be prevented because they lead to form unfavourable approach flow conditions, reducing the discharge capacity, and may compromise the dam safety. Therefore, a proper inlet channel design is very important for the spillway. The inlet channel delivers flow to the weir or cured crest, determining the amount of flow and flow conditions through the spillway. Therefore, the inlet channel must be hydraulically and structurally adequate in order to provide sufficient capacity.

The analysis of water flow in an inlet channel of a spillway is an important engineering

*Corresponding author (e-mail: *wangjibao@hhu.edu.cn*)
Received Jun. 8, 2009; accepted Dec. 9, 2009

problem. The Changjiang Water Resources Commission of the People's Republic of China (NDRC-PRC 2000) and the United States Army Corps of Engineers Waterways Experiment Station (USACE-WES) (USACE-WES 1952) studied water flow over spillways and developed a series of design charts, which were updated recently (USACE 1995). These charts and manuals aid in the design of a spillway profile for the given design flood condition. Many researchers have tried to solve the flow field with physical model-based experimental techniques (Tokmadzhyan et al. 1988; Aliev et al. 1987). Jian (2005) compared flow conditions with varying curves of the guide wall. Based on the physical model experiment, Guo and Wang (1998) defined the target optimization. Hua and Nan (2003) analyzed the optimal layout for a bank spillway.

The guide wall is a key factor in river flow through inlet channel structures of the riverbank spillway. The guide wall tends to cause flow separation, leading to a decrease of discharge capacity in the spillway. On the other hand, vortex formation can result in a resonance phenomenon, which may eventually lead to failure of the dam. This study focused on a physical model of the separation of flow and vortices near the guide wall when the spillway discharges flood flow, and on developing a more efficient type of guide wall for regulating the separation of flow in the inlet channel of the spillway.

2 Problem statement in project

2.1 General description of project

The Yutang Hydropower Station is located in the middle reaches of the Furong River in Guizhou Province, China. The maximum height of the dam is 75.5 m, and it has two turbine generator units of 37.5 MW. The left bank spillway, with a discharge capacity of 9 410.00 m^3/s at the reservoir level of 472.12 m, consists of an inlet channel, a control structure, a slope with a length of 274.00 m and a flat bottom (Fig. 1).

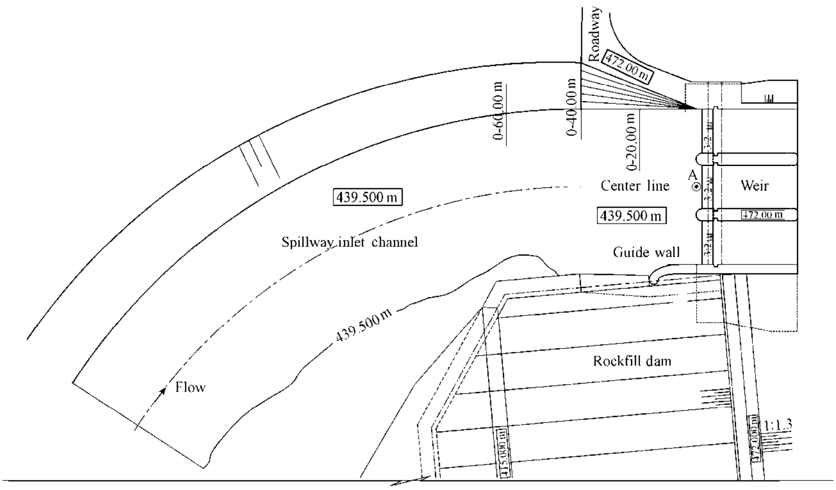

Fig. 1 Layout of inlet channel for bank spillway of Yutang Project

Three rectangle holes were made in the lock basin of the spillway. The size of each hole was 14.5 m × 16.0 m (width × height). The thickness of the pier is 4.0 m, the elevation of the inlet channel bed is 439.5 m, the elevation of the weir crest is 449.0 m, and the elevation of the sluice top is 472.5 m. The main gate is a radial gate.

The width of the inlet channel is 58.5 m, and the elevation of the channel bed is 443.5 m. The right guide wall of the inlet channel is also used as a dam cut-off wall, whose length is 18.0 m, width is 2.0 m, and height is 32.0 m. The profile of the head is an elliptic curve that can be expressed through the following equation:

$$\frac{x^2}{10}+\frac{y^2}{5}=1 \tag{1}$$

where x and y are the transverse and longitudinal axes, respectively.

The experiment was carried out with a hydraulic model of the whole Yutang Hydroelectric Power Station. The model scale ratio was 1:100. A propeller-type current meter was used to survey the speed of flow and a water level marking pin was used to survey water level.

2.2 Hydraulic analysis

The river flow is slow upstream of the dam, and the average velocity at the cross section upstream of the dam is 0.5 m/s. When the water level reaches 230.00 m far from the dam, the river begins to veer left little by little, and the turning radius is large. When flow is 111.00 m upstream of the dam, the river veers right and flows toward the spillway, but the turning radius is small. The angle between the flow direction and the dam axis is 45 degrees, and the average velocity at the cross section is 0.6-0.8 m/s. Then, the flow conditions change, with the flow velocity increasing rapidly and the direction of flow shifting to become parallel to the axis of the spillway. The velocity is 2.0-4.0 m/s in the section 0-60.00 m. At the same time, the flow velocity distribution over the cross section is non-uniform. Most of the flow passes through the left side of the channel, where the velocity and the direction of flow change faster than at the right side.

After the water enters the inlet channel, the direction of flow is parallel to the longitudinal axis of the spillway. The type of flow is a tranquil flow in the channel. The flow velocity increases quickly. The bottom velocity is 3.0-5.0 m/s in the section 0-40.00 m, and rapidly increases to 17-19 m/s at the section 0+00.00 m. The surface velocity increases from 2-4 m/s to 9-11 m/s. The value of the Froude number ranges from 0.20 to 0.44 in the inlet channel. Table 1 shows the flow details of the inlet channel.

Table 1 Flow details of inlet channel

Cross section	Velocity (m/s)	Water level (m)	Froude number
0-60.00m	3.8	27.34	0.23
0-40.00m	5.5	27.30	0.34
0-20.00m	7.0	26.14	0.44
0+00.00m	12.4	17.64	0.94

In particular, the cross sectional velocity on the right side of the straight guide wall of the spillway is larger due to the effect of contraction. At thirty meters upstream of the dam, the direction of flow is parallel to the axis of the dam. The velocity of flow decreases from 6 - 8 m/s to 1.0-1.5 m/s. When the water flows around the head of the guide wall, flow separation occurs. This results in a number of vortices at the upstream end of the guide wall, and directly affects the flow conditions in the inlet channel (Fig. 2). During a peak flood, the corresponding maximum value of the water surface concave depth is 7.62 m. This results in flow wave, and an extreme imbalance of flow distribution through the cross section in the inlet channel. When the water level reaches the high flood level of 471.83 m, the height of water is only 16 m at the inlet of the left hole, but 19 m at the inlet of the right hole. This results in more flood discharge from the right hole than from the left hole. Consequently, the actual discharge capacity doesn't meet that of the design. Hence, the chute spillway discharge and the rate of energy dissipation are also affected.

Fig. 2 Flow conditions at channel inlet with longitudinal guide wall

There are two main conditions that produce these flows:

(1) The velocity is high:

Generally, the approach velocity should be low in the spillway, less than 2.5 m/s, and the inner velocity should be less than 4.0 m/s in the channel (NDRC-PRC 2002). For high velocities, special problems regarding head loss and flow separation arise. In this study, however, the approach velocity reached 3.8 m/s at the section 0-60.00 m, 5.5 m/s at the section 0-40.00 m, and 7.0 m/s at the section 0-20.00 m in the inlet channel. In particular, the cross sectional average velocity at the head of the guide wall reached 3.4 m/s.

(2) The profile of the guide wall needs to be improved:

The structure of the inlet channel of the bank spillway is asymmetrical. Its left side is a shade wall and its right side is a straight guide wall. The length of the guide wall is only 18.0 m, approximately the same as the design flood flow depth. In general, the ratio of flood flow depth to the length of the guide wall should be about 2 to 3 (NDRC-PRC 2002). The profile of the guide wall at the channel inlet is not designed properly: it does not prevent the formation of vortices and separation of flow.

3 Improved study

3.1 First test

Because the structure of the spillway is not modified on the whole, the separation of flow and the formation of vortices are not prevented by widening the spillway to minimize the velocity. Analysis of the flow conditions shows that the guide wall has a significant effect on upstream flow conditions. Therefore, the main step needed for optimization of design is the modification of the profile of the guide wall at the inlet of the channel. The first step in improving the optimization of design is shown in Fig. 3.

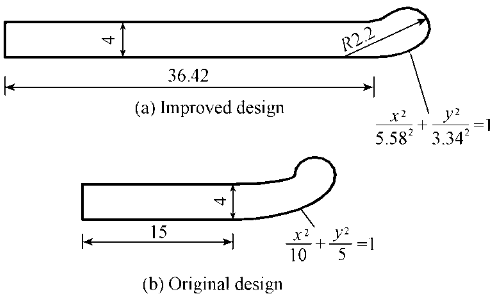

Fig. 3 Profile of guide wall (Unit: m)

Based on the experience of completed projects in China and elsewhere, the length of the guide wall along the river should be greater than twice the height of the design water head (NDRC-PRC 2002). The length of the guide wall of the Yutang project is the same as the design water head over the weir crest. Therefore, the length of the guide wall must be extended. Secondly, a square edge or a small radius-edge of the guide wall results in flow separation and formation of vortices. Compound curves consisting of two or more circular arcs and elliptical curves are often considered more suitable profiles. Thus, the improved design has an extended wall length of 33.15 m. This makes the total length of the guide wall about 1.8 times the height of the design water head. The curve of the guide wall head is also modified; it becomes a compound curve consisting of circular arcs and an ellipse (Fig.3), whose equation can be expressed as

$$\frac{x^2}{5.58^2}+\frac{y^2}{3.34^2}=1 \tag{2}$$

Tests show that the improved design makes flow conditions smooth at the inlet of the channel, which may make the river flow into the lock basin more regularly.

3.2 Second test

The study of guide wall improvement shows that the flow condition at the inlet of the channel is totally transformed after the wall is redesigned, but there is still some separation of flow and some larger vortices still form along the guide wall. Thus, it is necessary that special steps be taken to fully avoid or significantly weaken the separation of flow and the formation of vortices, ensuring a smooth flow condition in the channel.

After conducting an experimental study of the guide wall, it is evident that the flow separation may be prevented by putting slots in the guide wall. The submerged water may pass through these slots and adhere to the upper surface of the wall for its entire length. This may effectively prevent separation of flow, reduce the maximum value of the water surface fall height from 7.62 m to 2.52 m, and reduce the radius of the separation of flow from about 20 m to 5 m. This also weakens the vertical whirlpool along the side of the guide wall and upgrades the flow conditions of the channel, making the surface water less turbulent while causing the water to flow in a relatively balanced way through each of the holes of the spillway weir (Fig. 4). Finally, the value of the discharge coefficient increases by 0.01 (Table 2). The discharge coefficient *m* can be calculated as follows:

$$m = \frac{Q}{B\sqrt{2g}H^{3/2}} \tag{3}$$

where Q is the flow rate of the spillway, B is the width of the spillway weir, and H is the height of the liquid above the weir.

Fig. 4 Flow condition of inlet channel with improved guide wall

Table 2 Comparison of test results

Maximum water surface fall (m)		Discharge coefficient	
Original design	Improved design	Original design	Improved design
7.62	2.52	0.42	0.43

Note: These are values during design flood discharge through spillway.

According to the results of the test, holes with different opening sections and different ratios have different effects on the separation of flow. The test shows that ratios of opening holes from 50/100 to 70/100 should be suitable, and the top height of holes should be lower than the design water level while the bottom height of holes should be higher than the height of the weir. The pier profile should be a smooth curve. The profile of the guide wall is shown in Fig. 5.

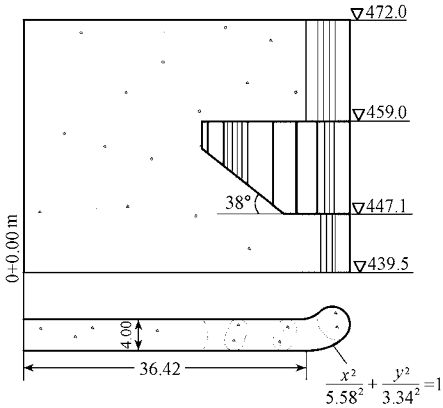

Fig. 5 Guide wall opening hole (Unit: m)

4 Conclusions and recommendations

In the physical model, vortices appear near the head of the guide wall while the flood is discharged. It is recommended that vortices be reduced to prevent any type of problem in the bank spillway. This study developed a new technique to do that. Different types of guide walls were tested, and a long guide wall with openings is the best design for eliminating vortices completely in front of the guide wall of the Yutang Dam.

It is recommended to focus first on assuring the safety of the Yutang Dam structure. Since the guide wall is a single straight wall with openings, it is necessary to calculate the stability to assure the safety of the wall.

At present, the guide wall with openings is only a case study, but the authors believe that this experience may be useful to engineers, in spite of the design method being somewhat unreasonable. As of now, a trial and error method is recommended to select this guide wall profile.

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